Recent developments in the Jülich model

S. Krewald

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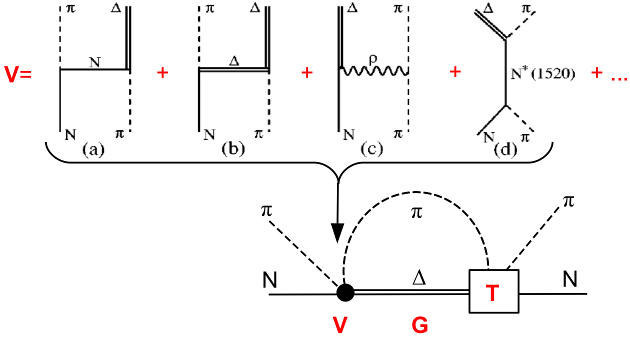
The Jülich model of meson-baryon interaction

Theoretical background

- Coupled channels πN, ηN, $K\Lambda$, $K\Sigma$; σN, ρN, $\pi\Delta$.
  (effective $\pi\pi N$ channels)
- Chiral Lagrangian of Wess and Zumino [PR163 (1967), Phys.Rept. 161 (1988)].
- Baryonic resonances up to $J = 7/2$ with derivative couplings.

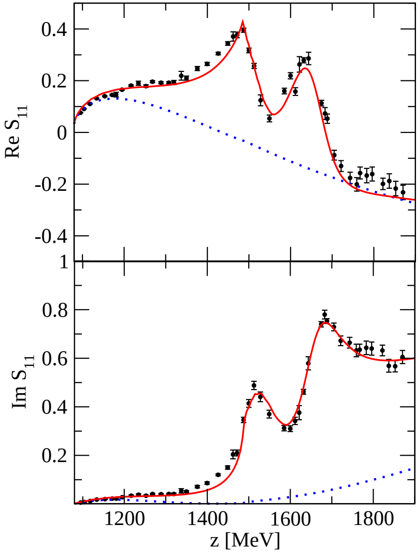
Scattering equation in the JLS basis

$$\langle L'S'k'|T^{IJ}_{\mu\nu}|LSk\rangle = \langle L'S'k'|V^{IJ}_{\mu\nu}|LSk\rangle$$
$$+ \sum_{\gamma, L''S''} \int_0^\infty k''^2\, dk'' \langle L'S'k'|V^{IJ}_{\mu\gamma}|L''S''k''\rangle \frac{1}{Z - E_\gamma(k'') + i\epsilon} \langle L''S''k''|T^{IJ}_{\gamma\nu}|LSk\rangle$$



The S_{11} partial wave in πN scattering

[Data: Arndt et al., FA08, EPJA 35 (2008)]



- Laurent series,

$$T^{(2)\,ij} = \frac{a_{-1}^{ij}}{z - z_0} + a_0^{ij} + \ldots$$

- Resonance interference of $N^*(1535)$ and $N^*(1650)$.

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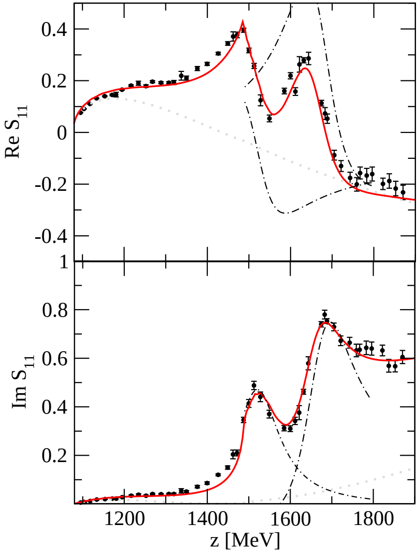

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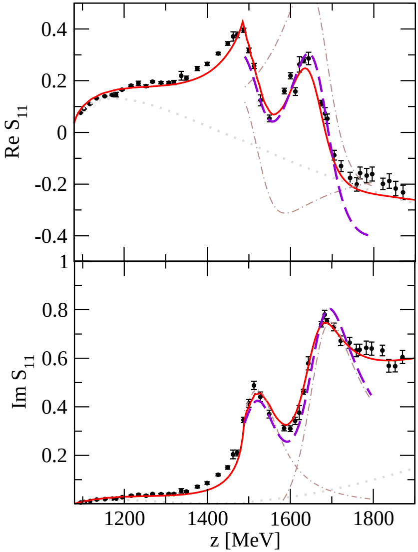

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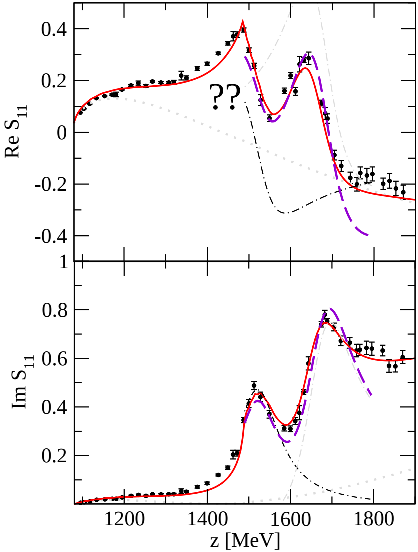

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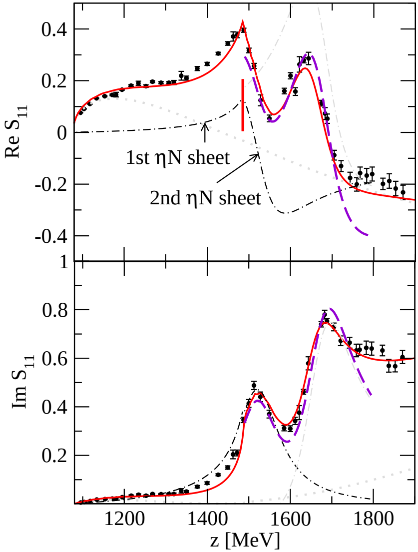

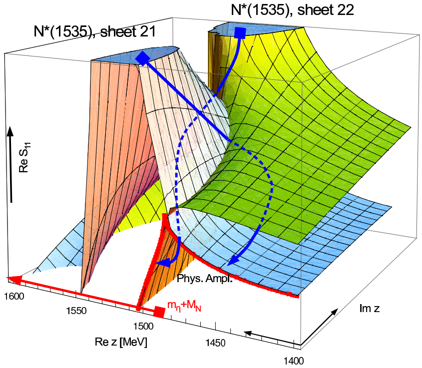

- Different poles on different sheets produce the cusp.

The S_{11} partial wave in πN scattering

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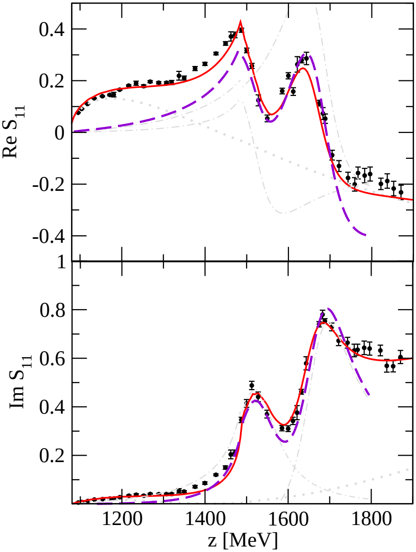
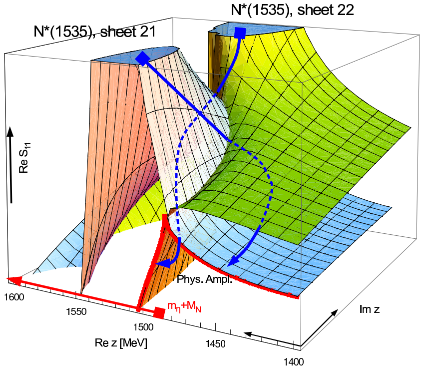




- Different poles on different sheets produce the cusp.

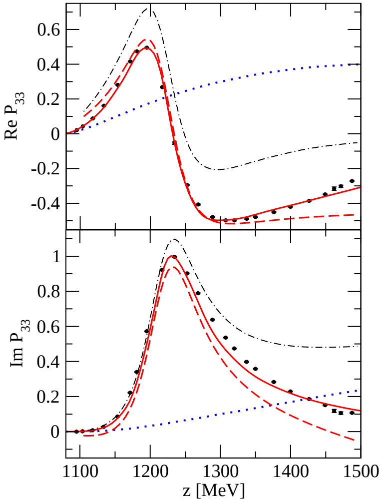
Zeros of T-matrix

Zeros of T in [MeV]. [FA02]: Arndt et al., PRC 69 (2004).

first sheet		second sheet		[FA02]
P_{11}	$1235 - 0\,i$	S_{11}	$1587 - 45\,i$	$1578 - 38\,i$
D_{33}	$1396 - 78\,i$	S_{31}	$1585 - 17\,i$	$1580 - 36\,i$
		P_{31}	$1848 - 83\,i$	$1826 - 197\,i$
		P_{13}	$1607 - 38\,i$	$1585 - 51\,i$
		P_{33}	$1702 - 64\,i$	–
		D_{13}	$1702 - 64\,i$	$1759 - 64\,i$

Zeros of full T-matrix :
information on poles and final state interaction.

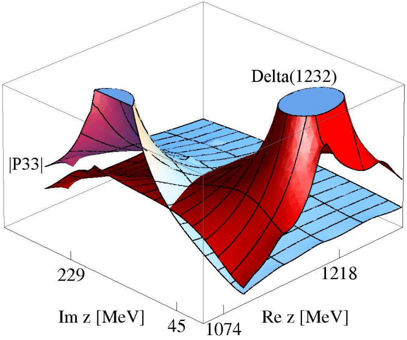
The non-pole T-matrix: P_{33}



- $T = T^{\mathrm{NP}} + T^{\mathrm{P}}$
- $T = \frac{a_{-1}}{z-z_0} + a_0 + \ldots$

$$a_0 = T^{\mathrm{NP}} + a_0^{\mathrm{P}}$$

$$a_0^{\mathrm{P}} = \frac{a_{-1}}{\Gamma_D \Gamma_D^{(\dagger)}} \left(\frac{\partial}{\partial z} (\Gamma_D \Gamma_D^{(\dagger)}) + \frac{a_{-1}}{2} \frac{\partial^2}{\partial z^2} \Sigma \right).$$



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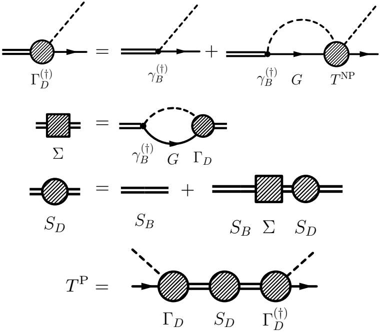
Couplings and dressed verticess

Residue a_{-1} vs. dressed vertex Γ vs. bare vertex γ.



$$a_{-1} = \frac{\Gamma_d \Gamma_d^{(\dagger)}}{1 - \frac{\partial}{\partial Z}\Sigma}$$
$$g = \sqrt{a_{-1}}$$
$$r = |(\Gamma_D - \gamma_B)/\Gamma_D|,$$
$$r' = |1 - \sqrt{1 - \Sigma'}|,$$

- Dressed Γ depends on $T^{\rm NP}$.
- $\sqrt{a_{-1}} \neq \Gamma \neq \gamma$

	γ^C	Γ^C	r [%]	r' [%]
$N^*(1520)\ D_{13}$	$6.4 - 0.6i$	$13.2 + 1.2i$	53	61
$N^*(1720)\ P_{13}$	$-0.1 + 5.4i$	$0.9 + 4.8i$	24	45
$\Delta(1232)\ P_{33}$	$1.3 + 13.0i$	$-2.8 + 22.2i$	45	40
$\Delta^*(1620)\ S_{31}$	$0.1 + 14.3i$	$5.0 + 5.7i$	130	66
$\Delta^*(1700)\ D_{33}$	$5.4 - 0.8i$	$6.7 + 1.0i$	33	54
$\Delta^*(1910)\ P_{31}$	$9.4 + 0.3i$	$1.9 - 3.2i$	222	22

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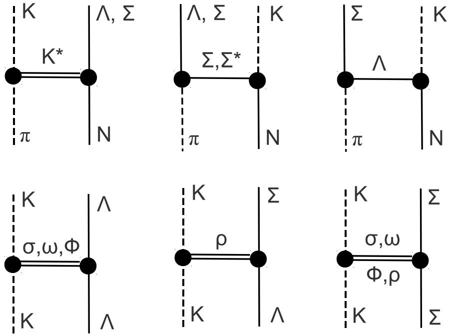
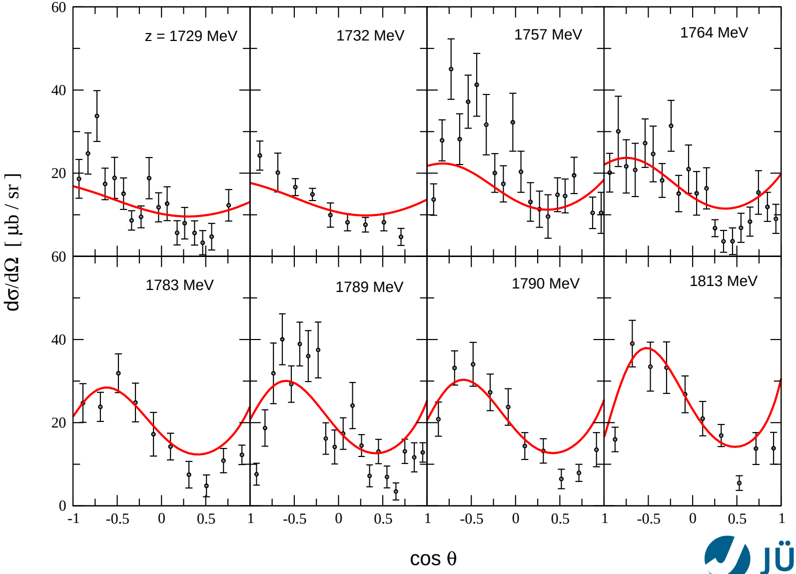
The reaction $\pi^+ p \to K^+\Sigma^+$

Towards a unified analysis of different final states

- $\pi^+ p \to K^+\Sigma^+$: Pure isospin $3/2$; few Δ resonances.
- SU(3) symmetry provides predictive power.
- Guiding principle in the fit: minimal set of Resonances.



Differential cross section of $\pi^+ p \to K^+ \Sigma^+$



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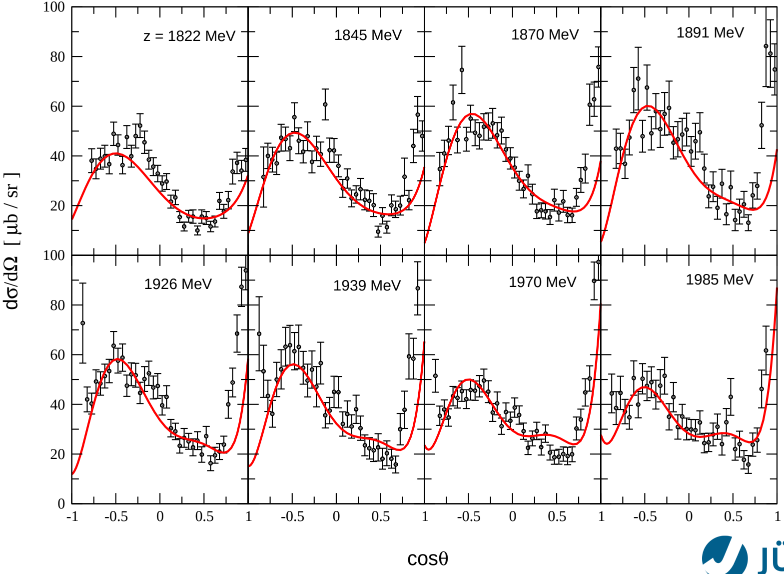

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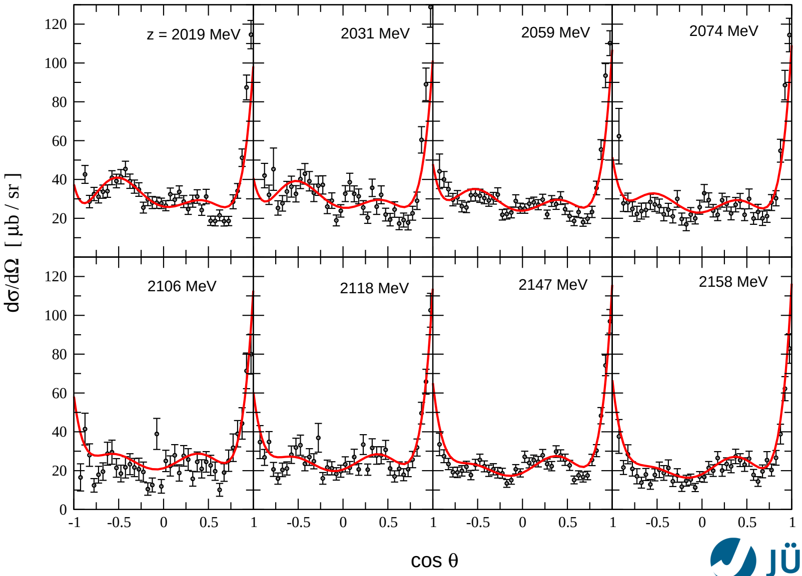

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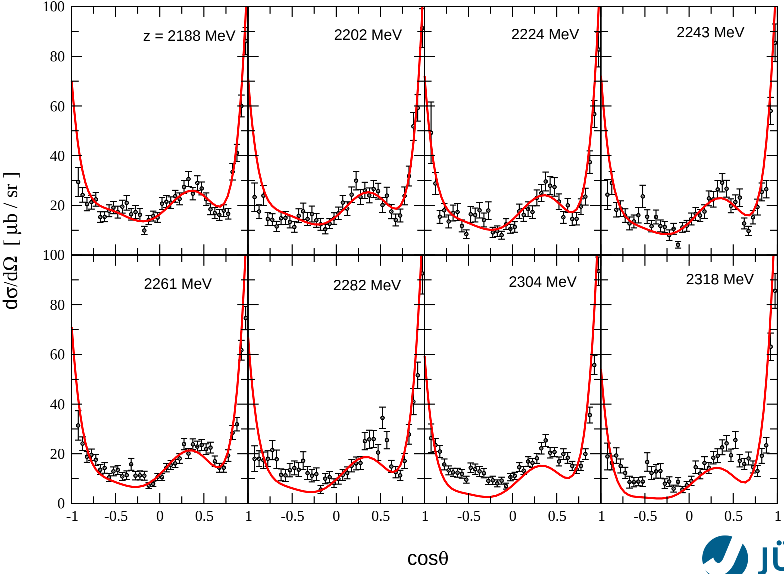
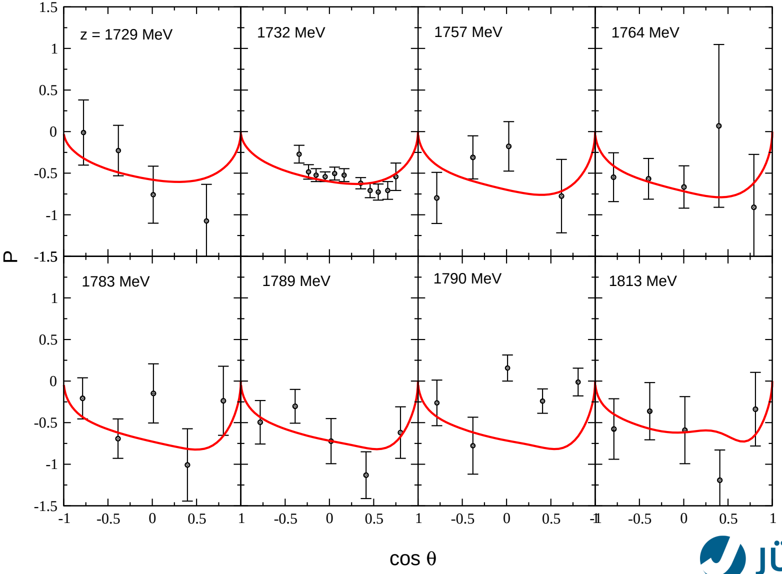
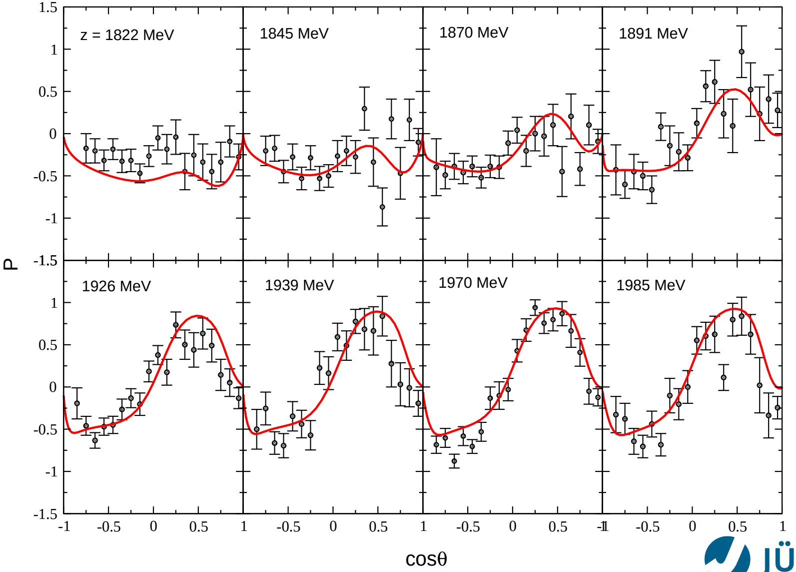


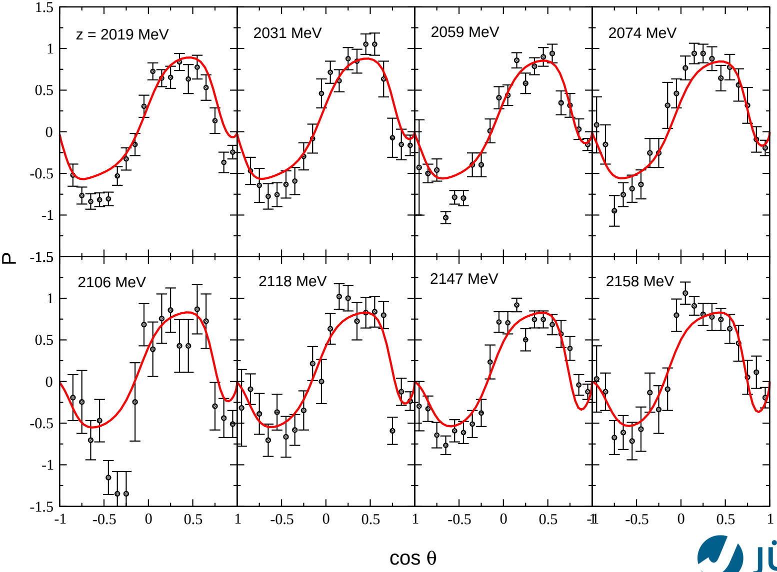
Polarization of $\pi^+ p \to K^+\Sigma^+$



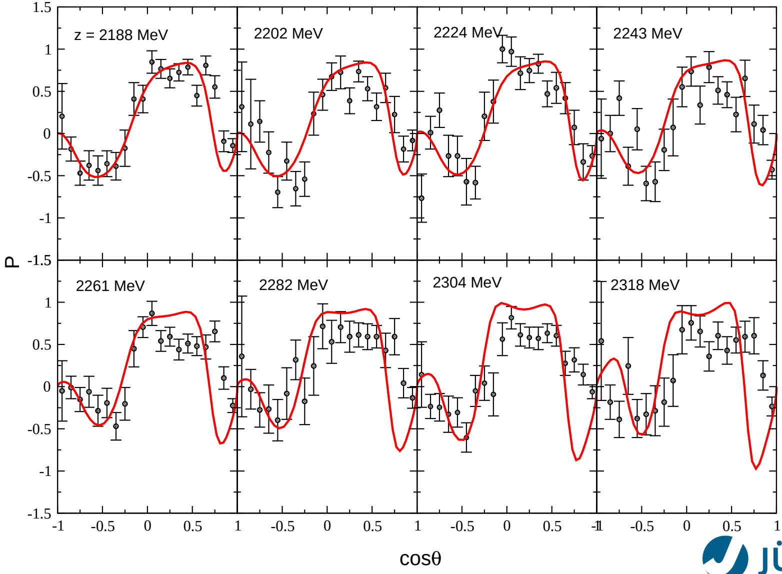
Polarization of $\pi^+ p \to K^+ \Sigma^+$



Polarization of $\pi^+ p \to K^+ \Sigma^+$

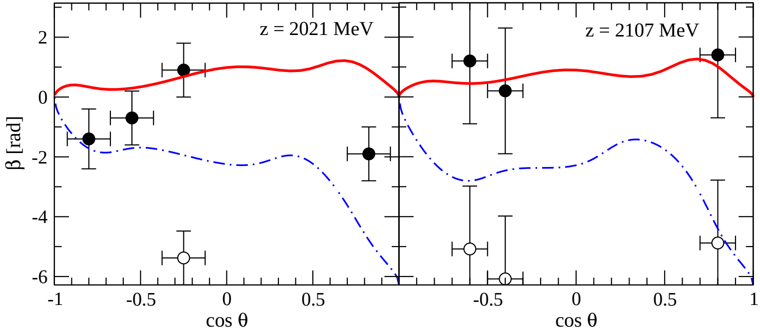


Polarization of $\pi^+ p \to K^+\Sigma^+$



Spin rotation parameter β of $\pi^+ p \to K^+\Sigma^+$

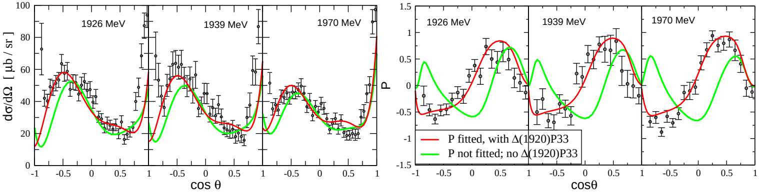
Definitions Observables



important to reduce ambiguities.

The importance of spin observables: $\Delta(1920)P_{33}$

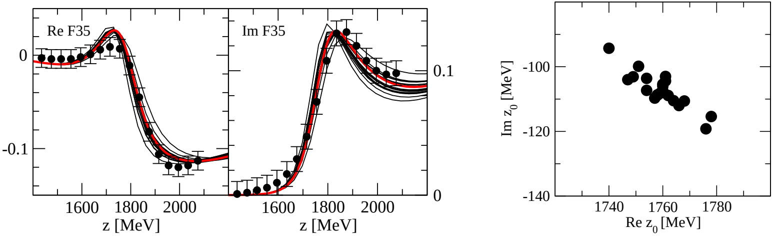
- $\Delta(1920)P_{33}$: invisible in $\pi N \to \pi N$, but needed in $\pi^+ p \to K^+ \Sigma^+$.
- GREEN: no $\Delta(1920)P_{33}$, fit elastic πN, $d\sigma/d\Omega(\pi^+ K^+)$, but NOT P).
  RED: $\Delta(1920)P_{33}$, fit elastic πN, $d\sigma/d\Omega(\pi^+ K^+)$ and P).



- Without polarization measurement P, one could have overlooked the $\Delta(1920)P_{33}$.

Error analysis: $\Delta(1905)F_{35}$

- Determination of the non-linear parameter error
  - $\chi^2 + 1$ criterion.
  - Varying 39 of 40 parameters to get parameter error.
- Get error on derived quantities like pole positions and residues.
- So far, simplified consideration (error from πN not available, because energy dependent GWU/SAID solution is fitted [PRC74 (2006)]).



Error estimates for masses: $\Delta(1905)F_{35}$

Table: Error estimates of bare mass m_b and bare coupling f for the $\Delta(1905)F_{35}$ resonance.

m_b [MeV]	πN	ρN	$\pi\Delta$	ΣK
2258^{+44}_{-43}	$0.0500^{+0.0011}_{-0.0012}$	$-1.62^{+1.29}_{-1.61}$	$-1.15^{+0.030}_{-0.022}$	$0.120^{+0.0065}_{-0.0059}$

Table: Error estimates of pole position and residues for the $\Delta(1905)F_{35}$ resonance.

			$\pi N \to \pi N$	$\pi N \to K\Sigma$
Re z_0 [MeV]	1764^{+18}_{-20}	$\|r\|$ [MeV]	$11^{+1.7}_{-1.4}$	$1.4^{+0.24}_{-0.21}$
Im z_0 [MeV]	-109^{+13}_{-12}	θ [^{0}]	$-45^{+3.8}_{-11}$	$-313^{+4.2}_{-10}$

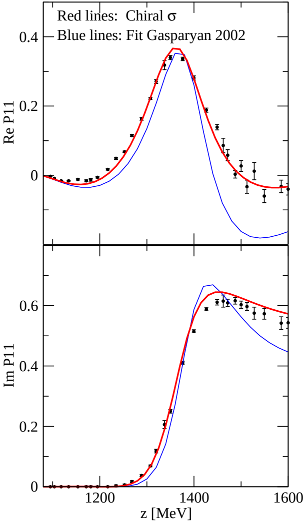
Resonance content from $\pi N \to \pi N$ plus $\pi^+ p \to K^+\Sigma^+$

	Re z_0 [MeV] / -2 Im z_0 [MeV]	$\lvert r \rvert$ [MeV] / θ [^{0}]	$(\Gamma_{\pi N}^{1/2}\Gamma_{K\Sigma}^{1/2})/\Gamma_{\text{tot}}$ [%] This study	Candlin (1983)	Gießen (2004)
$\Delta(1905)F_{35}$	1764	1.4	1.23	1.5(3)	<1
$5/2^+$ ****	218	-313			
$\Delta(1910)P_{31}$	1721	5.5	2.98	<3	1.1
$1/2^+$ ****	323	-6			
$\Delta(1920)P_{33}$	1884	5.9	5.07	5.2(2)	2.1(3)
$3/2^+$ ***	229	-38			
$\Delta(1930)D_{35}$	1865	1.6	2.14	<1.5	
$5/2^-$ ***	147	-43			
$\Delta(1950)F_{37}$	1873	2.7	2.54	5.3(5)	—
$7/2^+$ ****	206	-255			

Summary

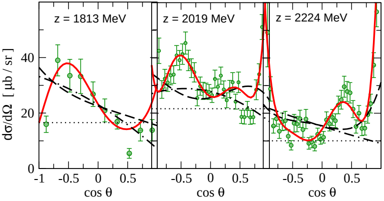
- Analytical Structure:
  Poles, residues, branch points, zeros.
- Interpretation: model insensitive quantities
  dressed vertices
- Results: coupled channel approach applied for energies below 2.2GeV.
  Room for more resonances!
  ERROR ANALYSIS
- In progress:
  KΛ, KΣ
  Photoproduction, Electroproduction.
  Determine Lagrangian coupling constants directly from data analysis.

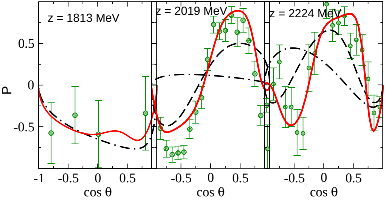
Chiral sigma, P_{11}



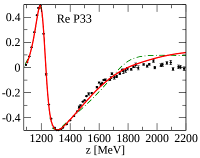
The reaction $\pi^+ p \to K^+ \Sigma^+$

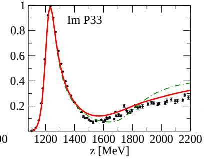
M.D., C. Hanhart, F. Huang, S. Krewald, U.-G. Meißner, D. Rönchen, [NPA851 (2011)]

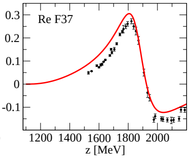


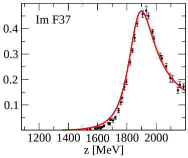


Data upper: Candlin 1983, NPB 226 (1983), lower: GWU/SAID, PRC74 (2006)









Couplings “ $g = \sqrt{a_{-1}}$ ” to other channels

back

	$N\pi$		$N\rho^{(1)}$ $(S = 1/2)$		$N\rho^{(2)}$ $(S = 3/2)$		$N\rho^{(3)}$ $(S =$	
$N^*(1535)\ S_{11}$	S_{11}	$8.1 + 0.5i$	S_{11}	$2.2 - 5.4i$	–		D_{11}	0.5
$N^*(1650)\ S_{11}$	S_{11}	$8.6 - 2.8i$	S_{11}	$0.9 - 9.1i$	–		D_{11}	0.3
$N^*(1440)\ P_{11}$	P_{11}	$11.2 - 5.0i$	P_{11}	$-1.3 + 3.2i$	P_{11}	$3.6 - 2.6i$	–	
$\Delta^*(1620)\ S_{31}$	S_{31}	$2.9 - 3.7i$	S_{31}	$0.0 - 0.0i$	–		D_{31}	0.0
$\Delta^*(1910)\ P_{31}$	P_{31}	$1.2 - 3.5i$	P_{31}	$0.2 - 0.4i$	P_{31}	$-0.2 - 0.4i$	–	
$N^*(1720)\ P_{13}$	P_{13}	$3.7 - 2.6i$	P_{13}	$0.1 + 0.8i$	P_{13}	$-1.1 + 0.1i$	F_{13}	0.1
$N^*(1520)\ D_{13}$	D_{13}	$8.4 - 0.8i$	D_{13}	$-0.6 + 0.7i$	D_{13}	$0.9 - 2.0i$	S_{13}	-2.5
$\Delta(1232)\ P_{33}$	P_{33}	$17.9 - 3.2i$	P_{33}	$-1.3 - 0.8i$	P_{33}	$-0.9 - 3.0i$	F_{33}	0.0
$\Delta^*(1700)\ D_{33}$	D_{33}	$4.9 - 1.0i$	D_{33}	$-0.2 + 0.9i$	D_{33}	$-0.4 - 0.4i$	S_{33}	-0.1

	$N\eta$		$\Delta\pi^{(1)}$		$\Delta\pi^{(2)}$		$N\sigma$	
$N^*(1535)\ S_{11}$	S_{11}	$11.9 - 2.3i$	–		D_{11}	$-5.9 + 4.8i$	P_{11}	-1.4
$N^*(1650)\ S_{11}$	S_{11}	$-3.0 + 0.5i$	–		D_{11}	$4.3 + 0.4i$	P_{11}	-2.1
$N^*(1440)\ P_{11}$	P_{11}	$-0.1 + 0.0i$	P_{11}	$-4.6 - 1.7i$	–		S_{11}	-8.3
$\Delta^*(1620)\ S_{31}$	–		–		D_{31}	$11.1 - 4.0i$	–	
$\Delta^*(1910)\ P_{31}$	–		P_{31}	$15.0 - 0.3i$	–		–	
$N^*(1720)\ P_{13}$	P_{13}	$-7.7 + 5.5i$	P_{13}	$-14.1 + 3.0i$	F_{13}	$0.0 - 0.3i$	D_{13}	-0.8
$N^*(1520)\ D_{13}$	D_{13}	$0.16 - 0.60i$	D_{13}	$0.0 + 0.4i$	S_{13}	$-12.9 - 0.7i$	P_{13}	-0.6
$\Delta(1232)\ P_{33}$	–		P_{33}	$-(4\text{ to }5) + i(0\text{ to }0.5)$	F_{33}	~ 0	–	
$\Delta^*(1700)\ D_{33}$	–		D_{33}	$-0.7 - 0.3i$	S_{33}	$-19.7 + 4.5i$	–	

Resonance couplings g_i $[10^{-3}\,\mathrm{MeV}^{-1/2}]$ to the coupled channels i. Also, the LJS type of each coupling is indicated. For the ρN channels, the total spin S is also indicated.

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first sheet		second sheet		[FA02]
P_{11}	$1235 - 0\,i$	S_{11}	$1587 - 45\,i$	$1578 - 38\,i$
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		P_{33}	$1702 - 64\,i$	–
		D_{13}	$1702 - 64\,i$	$1759 - 64\,i$

Position of zeros of the full amplitude T in [MeV]. [FA02]: Arndt et al., PRC 69 (2004).

	$\Gamma_{\pi N}/\Gamma_{\rm Tot}$ [%]	$\Gamma_{\eta N}/\Gamma_{\rm Tot}$ [%]
$N^*(1535)\ S_{11}$	48 [33 to 55]	38 [45 to 60]
$N^*(1650)\ S_{11}$	79 [60 to 95]	6 [3 to 10]
$N^*(1440)\ P_{11}$	64 [55 to 75]	0 $[0 \pm 1]$
$\Delta^*(1620)\ S_{31}$	34 [20 to 30]	–
$\Delta^*(1910)\ P_{31}$	11 [15 to 30]	–
$N^*(1720)\ P_{13}$	13 [10 to 20]	38 $[4 \pm 1]$
$N^*(1520)\ D_{13}$	67 [55 to 65]	0.10 $[0.23 \pm 0.04]$
$\Delta(1232)\ P_{33}$	100 [100]	–
$\Delta^*(1700)\ D_{33}$	13 [10 to 20]	–

Branching ratios into πN and ηN. The values in brackets are from the PDG, [Amsler et al., PLB 667 (2008)].

g_{fi} und h_{fi} in JLS-Basis:

$$g_{fi} = \frac{1}{2\sqrt{k_f k_i}} \sum_j (2j+1)\, d^j_{\frac{1}{2}\frac{1}{2}}(\theta) \left[\tau^{j(j-\frac{1}{2})\frac{1}{2}} + \tau^{j(j+\frac{1}{2})\frac{1}{2}} \right] \cos\frac{\theta}{2} + \frac{1}{2\sqrt{k_f k_i}} \sum_j (2j+1)\, d^j_{-\frac{1}{2}\frac{1}{2}}(\theta) \left[\tau^{j(j-\frac{1}{2})\frac{1}{2}} - \tau^{j(j+\frac{1}{2})\frac{1}{2}} \right] \sin\frac{\theta}{2}$$

$$h_{fi} = \frac{-i}{2\sqrt{k_f k_i}} \sum_j (2j+1)\, d^j_{\frac{1}{2}\frac{1}{2}}(\theta) \left[\tau^{j(j-\frac{1}{2})\frac{1}{2}} + \tau^{j(j+\frac{1}{2})\frac{1}{2}} \right] \sin\frac{\theta}{2} + \frac{i}{2\sqrt{k_f k_i}} \sum_j (2j+1)\, d^j_{-\frac{1}{2}\frac{1}{2}}(\theta) \left[\tau^{j(j-\frac{1}{2})\frac{1}{2}} - \tau^{j(j+\frac{1}{2})\frac{1}{2}} \right] \cos\frac{\theta}{2}$$

$$
\begin{aligned}
\frac{d\sigma}{d\Omega} &= \frac{k_f}{k_i}(|g_{fi}|^2 + |h_{fi}|^2) \\
&= \frac{1}{2k_i^2}\frac{1}{2}\cdot\left(\left|\sum_j (2j+1)(\tau^{j(j-\frac{1}{2})\frac{1}{2}} + \tau^{j(j+\frac{1}{2})\frac{1}{2}})\cdot d^j_{\frac{1}{2}\frac{1}{2}}(\Theta)\right|^2\right. \\
&\left. + \left|\sum_j (2j+1)(\tau^{j(j-\frac{1}{2})\frac{1}{2}} - \tau^{j(j+\frac{1}{2})\frac{1}{2}})\cdot d^j_{-\frac{1}{2}\frac{1}{2}}(\Theta)\right|^2\right)
\end{aligned}
$$

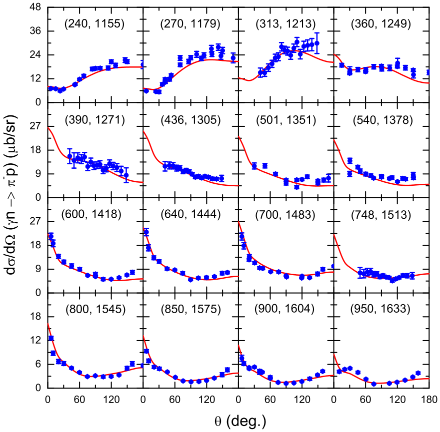
$$
\vec{P}_f = \frac{2Re(g_{fi}h^*_{fi})}{|g_{fi}|^2 + |h_{fi}|^2}\cdot\hat{n}
$$

$$
\beta = \arctan\left(\frac{2Im(h^*_{fi}g_{fi})}{|g_{fi}|^2 - |h_{fi}|^2}\right)
$$

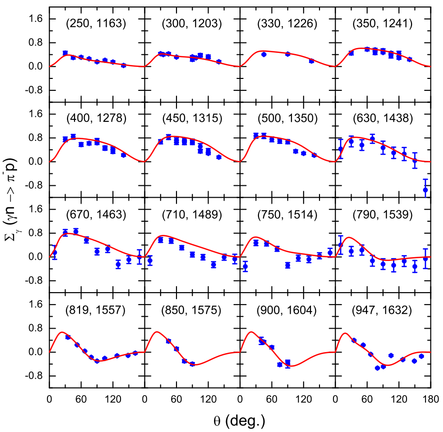
$d\sigma/d\Omega$ and Σ_γ for $\gamma n \to \pi^- p$

preliminary

back



Differential cross section for $\gamma n \to \pi^- p$

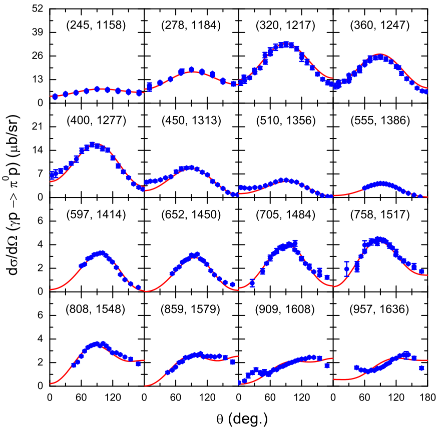


Photon spin asymmetry for $\gamma n \to \pi^- p$

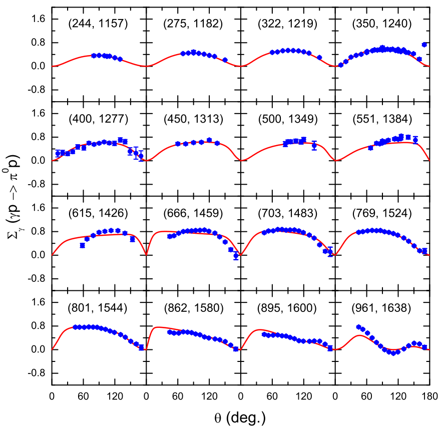
$d\sigma/d\Omega$ and Σ_γ for $\gamma p \to \pi^0 p$

preliminary

back



Differential cross section for $\gamma p \to \pi^0 p$



Photon spin asymmetry for $\gamma p \to \pi^0 p$

Hadronic approaches to QCD

χ Pert. Theory

- Systematic expansion in p, m.
- Perturbative unitarity.
- Low energy.

χ unitary approaches

- Systematics lost.
- Unitarity gained.
- Usually restriction to S-wave.
  $\rightarrow$ limited tool for data analysis.
- Dynamical generation of resonances.
  $\sigma(600)$, $f_0(980)$, $\Lambda(1405)$, $\cdots$
  (Lutz, Meißner, Oller, Oset, Pelaez, Weise,...)
- Including NLO contributions in a "true" solution of the BSE (Mai, Meißner,...).

Dynamical CC models

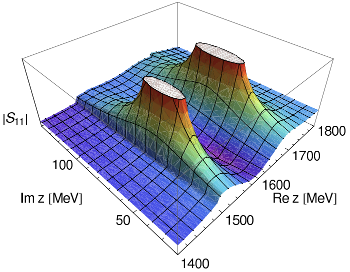
- Unitarity, dispersive parts.
- Lagrangian based, field theoretical approach.
- Chiral constraints.
- Dynamical generation of resonances plus genuine s-channel states.
- practical restrictions as data analysis tool.
- EBAC, DMT, Jülich, Nijmegen,...

K matrix approaches

- Unitarity.
- No dispersive parts.
- Lagrangian based (Gießen, Groningen,...).
- ...or phenomenological (Bonn-Gatchina).
- Partial wave analyses (GWU/Said).
- Most flexible tool for data analysis.

Poles and residues: Parameterization of the resonance content

[M.D., C. Hanhart, F. Huang, S. Krewald and U.-G. Meißner, NPA 829 (2009), PLB 681 (2009)]



	Re z_0 [MeV]	-2 Im z_0 [MeV]	$\|R\|$ [MeV]	θ [deg] [^{0}]
$N^*(1440)\ P_{11}$	1387	147	48	-64
ARN	1359	162	38	-98
HOE	1385	164	40	
CUT	1375±30	180±40	52±5	-100±35
$N^*(1520)\ D_{13}$	1505	95	32	-18
ARN	1515	113	38	-5
HOE	1510	120	32	-8
CUT	1510±5	114±10	35±2	-12±5

	Re z_0 [MeV]	-2 Im z_0 [MeV]	$\|R\|$ [MeV]	θ [deg] [^{0}]
$N^*(1535)\ S_{11}$	1519	129	31	-3
ARN	1502	95	16	-16
HOE	1487			
CUT	1510±50	260±80	120±40	+15±45
$N^*(1650)\ S_{11}$	1669	136	54	-44
ARN	1648	80	14	-69
HOE	1670	163	39	-37
CUT	1640±20	150±30	60±10	-75±25
$N^*(1720)\ P_{13}$	1663	212	14	-82
ARN	1666	355	25	-94
HOE	1686	187	15	
CUT	1680±30	120±40	8±12	-160±30
$\Delta(1232)\ P_{33}$	1218	90	47	-37
ARN	1211	99	52	-47
HOE	1209	100	50	-48
CUT	1210±1	100±2	53±2	-47±1
$\Delta^*(1620)\ S_{31}$	1593	72	12	-108
ARN	1595	135	15	-92
HOE	1608	116	19	-95
CUT	1600±15	120±20	15±2	-110±20
$\Delta^*(1700)\ D_{33}$	1637	236	16	-38
ARN	1632	253	18	-40
HOE	1651	159	10	
CUT	1675±25	220±40	13±3	-20±25
$\Delta^*(1910)\ P_{31}$	1840	221	12	-153
ARN	1771	479	45	+172
HOE	1874	283	38	
CUT	1880±30	200±40	20±4	-90±30

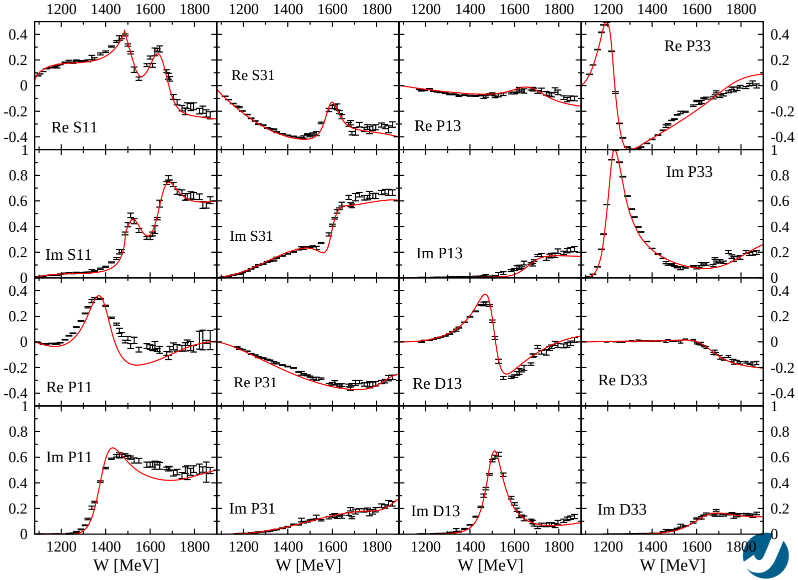
[ARN]: Arndt et al., PRC 74 (2006), [HOE]: Höhler, πN Newsl. 9 (1993), [CUT]: Cutkowski et al., PRD 20 (1979).

Residues to ηN, σN, ρN, $\pi\Delta$. Zeros. Branching ratios to πN, ηN.

JÜLICH FORSCHUNGSZENTRUM

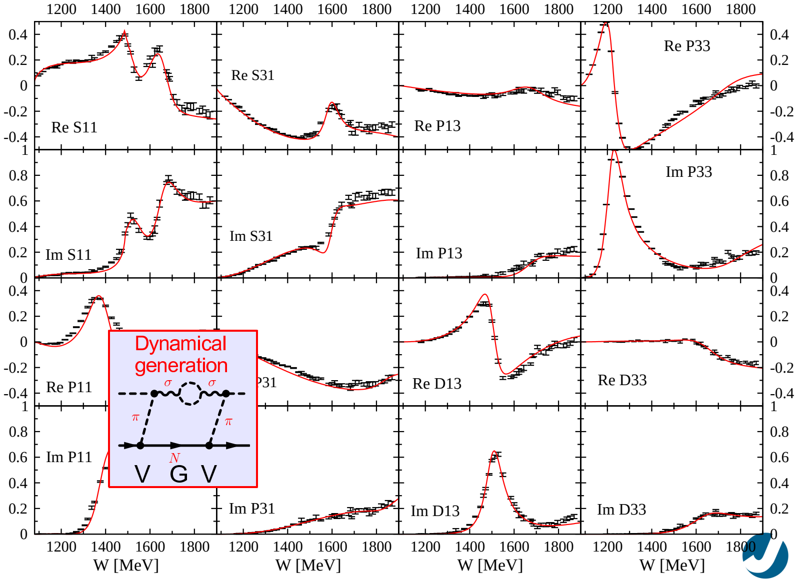
Some partial waves in $\pi N \to \pi N$

Jülich approach, solution 2002; “Data”: GWU/SAID, PRC74 (2006)



Some partial waves in $\pi N \to \pi N$

Jülich approach, solution 2002; "Data": GWU/SAID, PRC74 (2006)

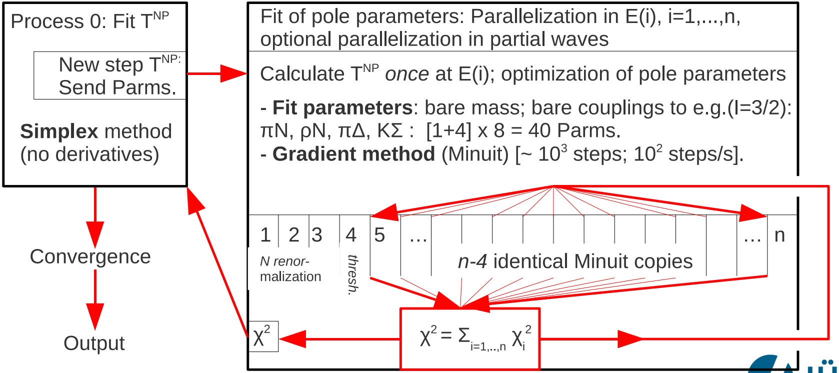


Parallelization [Project *JIKP07* on JUROPA/FZ Jülich, 384,000 CPU hours granted]

Fixing free parameters from s-channel "pole" processes [fast!] and $t-$, $u-$ processes [$\sim$ 100 x slower]

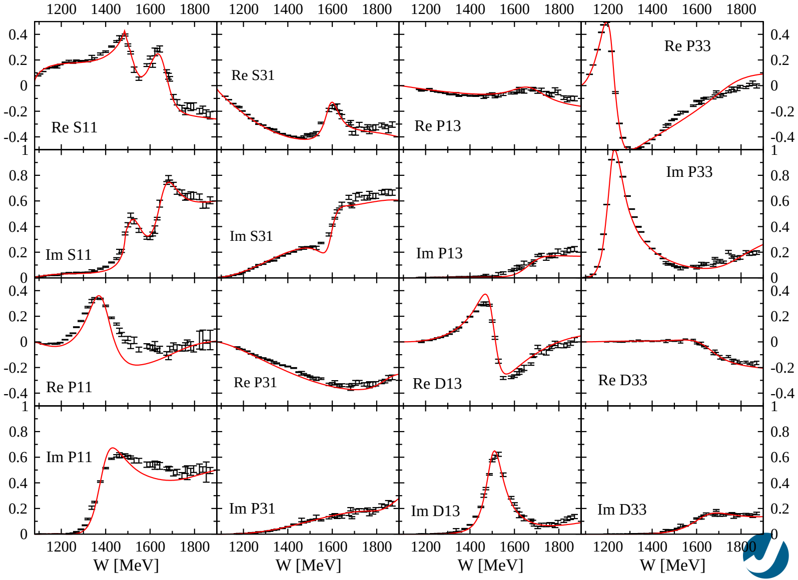
Requirements:

1) Maintain speed advantage of (x 100) of calculation of T^P from T^{NP} ($T=T^{NP}+T^P$)
   - > 2 nested Minuit runs: full fit of T^P [~40 parms.] for every step in T^{NP}
   - > requires separated memory spaces/ **mpi** parallelization on **Juropa/FZ Julich**
2) Scaling with # processes
3) Adding large amounts of data to χ^2 without increase of execution time



Partial waves in $\pi N \to \pi N$ (Solution 2002)

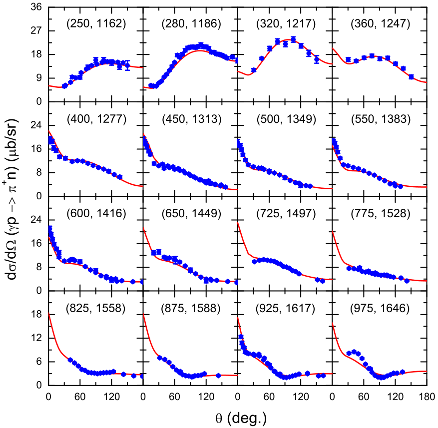
"Data": GWU/SAID, PRC74 (2006)



Linking reactions: $d\sigma/d\Omega$ and Σ_γ for $\gamma p \to \pi^+ n$

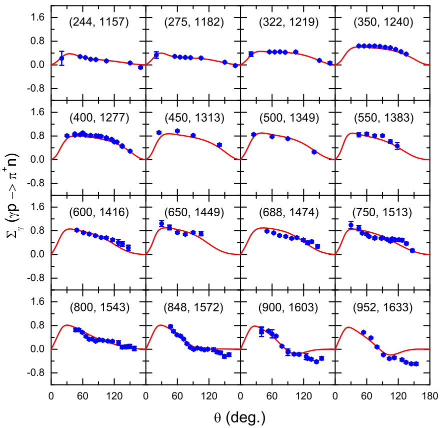
F. Huang, M.D., K. Nakayama, *et al.*, in prep. (see also arXiv:1103.2065)

Gauge invariance respected | Further results $\gamma N \to \pi N$



Differential cross section for $\gamma p \to \pi^+ n$

Data: CNS Data analysis center [CBELSA/TAPS, JLAB, MAMI,...]



Photon spin asymmetry for $\gamma p \to \pi^+ n$

- Different reaction channels provide more information on resonance content than higher precision in one channel.
- SU(3) symmetry provides predictive power.
- Linking partial waves and different reactions puts more constraints on the resonance content.
- $\pi^+ p \to K^+ \Sigma^+$: Pure isospin $3/2$; relatively few Δ resonances.
- Simultaneous fit to $\pi N \to \pi N$ partial waves [energy dependent GWU SAID solution, PRC74 (2006)] plus $\pi^+ p \to K^+ \Sigma^+$ observables.
- Guiding principle in the fit: Resonances are the last resort (while technically being the easiest way to improve the χ^2).
- Error analysis on pole positions is crucial.